MSFC-527

COMSOL Conference 2007

New Methods for the Adsorption of Carbon Dioxide and Water Vapor from Manned Spacecraft Atmospheres: Applications and Modeling

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NASA’s Vision for Space Exploration

- Mankind will once again travel beyond the confines of earth’s gravity, this time to remain there (on the moon and Mars) for extended periods.

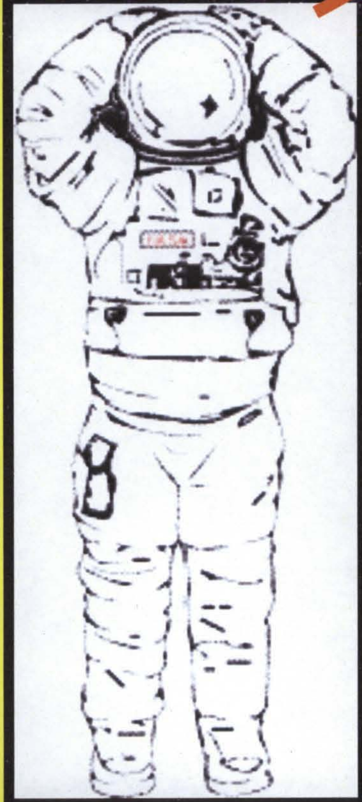
NASA's Vision for Space Exploration

- These missions will place unprecedented demands on launch systems.
- We must not only blast out of earth's gravity well as during the Apollo moon missions, but also launch the supplies needed to sustain a larger crew over much longer periods.

NASA’s Vision for Space Exploration

- All spacecraft systems must be minimized with respect to mass, power, and volume.
- Emphasis is also placed on system robustness to minimize replacement parts and ensure crew safety where a quick return to earth is not possible.

Human Metabolic Requirements for Life Support



Needs

Oxygen = 0.84 kg (1.84 lb)
Food Solids = 0.62 kg (1.36 lb)
Water in Food = 1.15 kg (2.54 lb)
Food Prep Water = 0.76 kg (1.67 lb)
Drink = 1.62 kg (3.56 lb)
Metabolized Water = 0.35 kg (0.76 lb)
Hand/Face Wash Water = 4.09 kg (9.00 lb)
Shower Water = 2.73 kg (6.00 lb)
Urinal Flush = 0.49 kg (1.09 lb)
Clothes Wash Water = 12.50 kg (27.50 lb)
Dish Wash Water = 5.45 kg (12.00 lb)
Total = 30.60 kg (67.32 lb)

Effluents

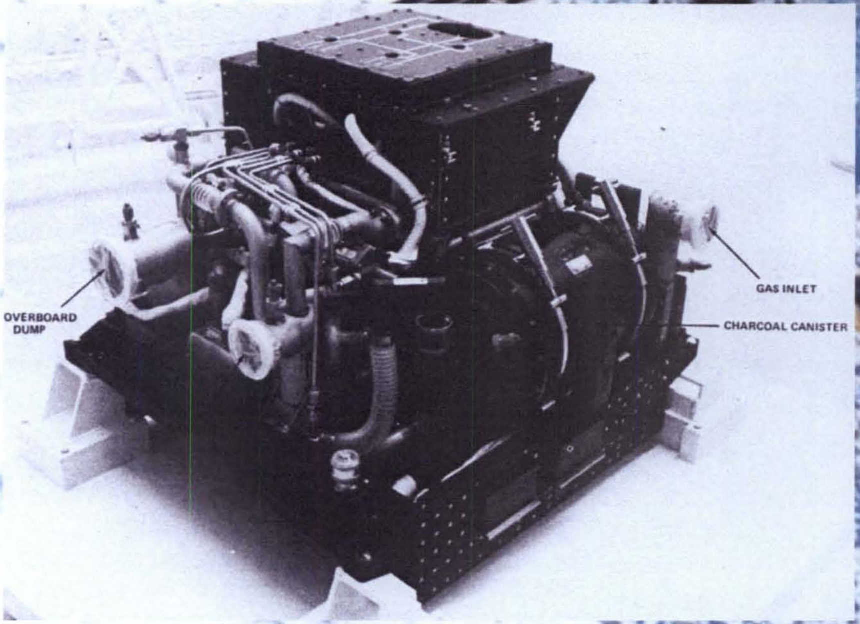
Carbon Dioxide = 1.00 kg (2.20 lb)
Respiration & Perspiration Water = 2.28 kg (5.02 lb)
Food Preparation, Latent Water = 0.036 kg (0.08 lb)
Urine = 1.50 kg (3.31 lb)
Urine Flush Water = 0.50 kg (1.09 lb)
Feces Water = 0.091 kg (0.20 lb)
Sweat Solids = 0.018 kg (0.04 lb)
Urine Solids = 0.059 kg (0.13 lb)
Feces Solids = 0.032 kg (0.07 lb)
Hygiene Water = 12.58 kg (27.68 lb)
Clothes Wash Water
Liquid = 11.90 kg (26.17 lb)
Latent = 0.60 kg (1.33 lb)
Total = 30.60 kg (67.32 lb)

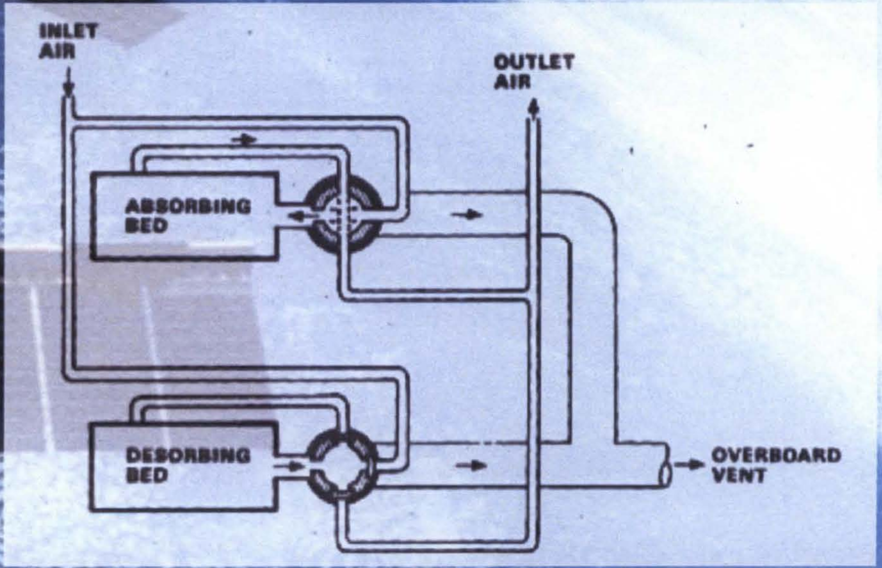
Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 BTU/person/day) and a respiration quotient of 0.87. The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO_2 generated to O_2 consumed.

SKYLAB IN ORBIT AT END OF MISSION

Historical Spacecraft Carbon Dioxide and Humidity Removal Systems

- Skylab was the United States first space station, with three manned missions totaling 171 days in the early 1970's.
- Molecular Sieves 13X and 5A were successfully used for CO_2 and H_2O removal on Skylab for 171 days without hardware anomaly.
- 70% of metabolic water and 100% of metabolic CO_2 for 3 crew was removed via a regenerable vacuum swing adsorption process.
- Three 2BMS units would provide sufficient removal for 6 non-exercising crew.





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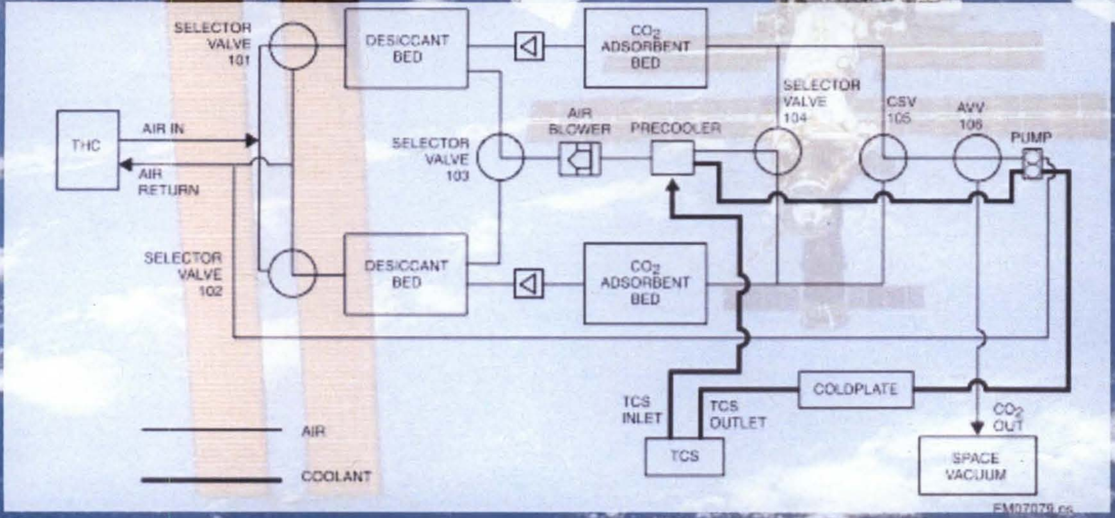
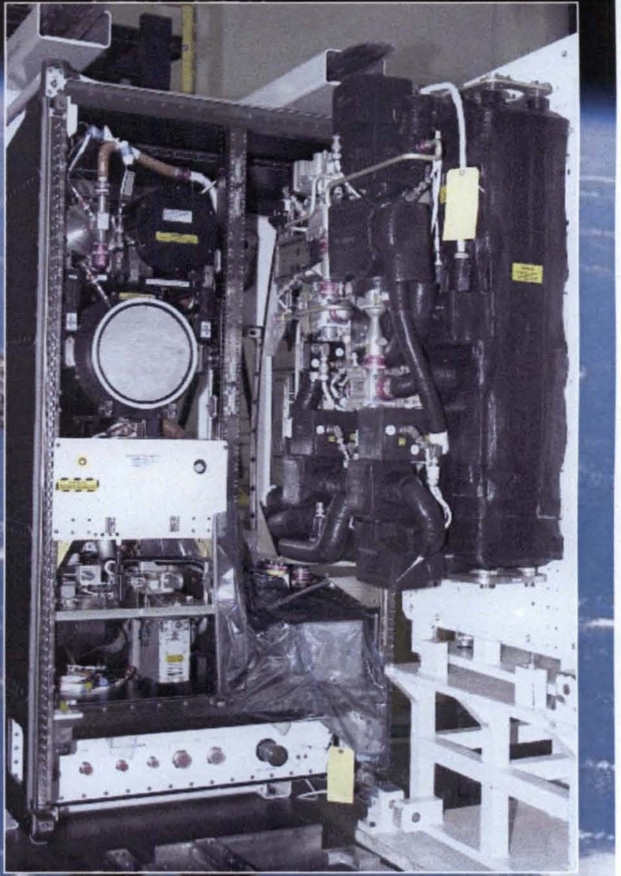
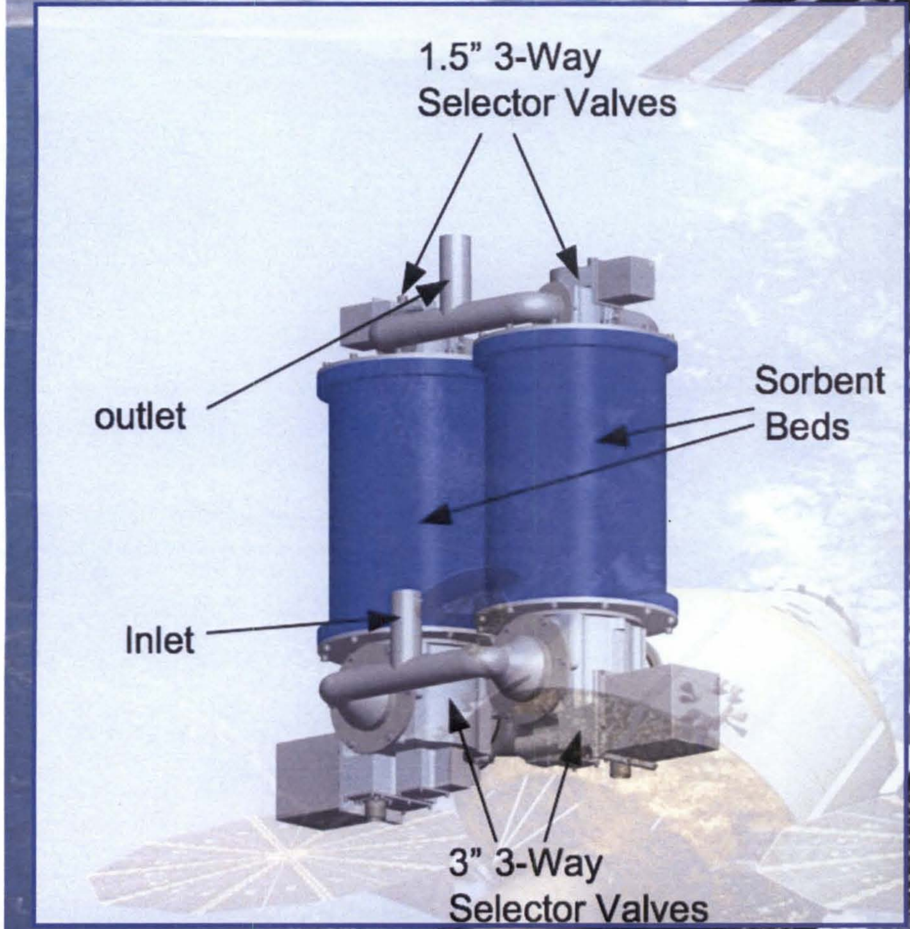
Current Spacecraft Carbon Dioxide and Humidity Removal Systems

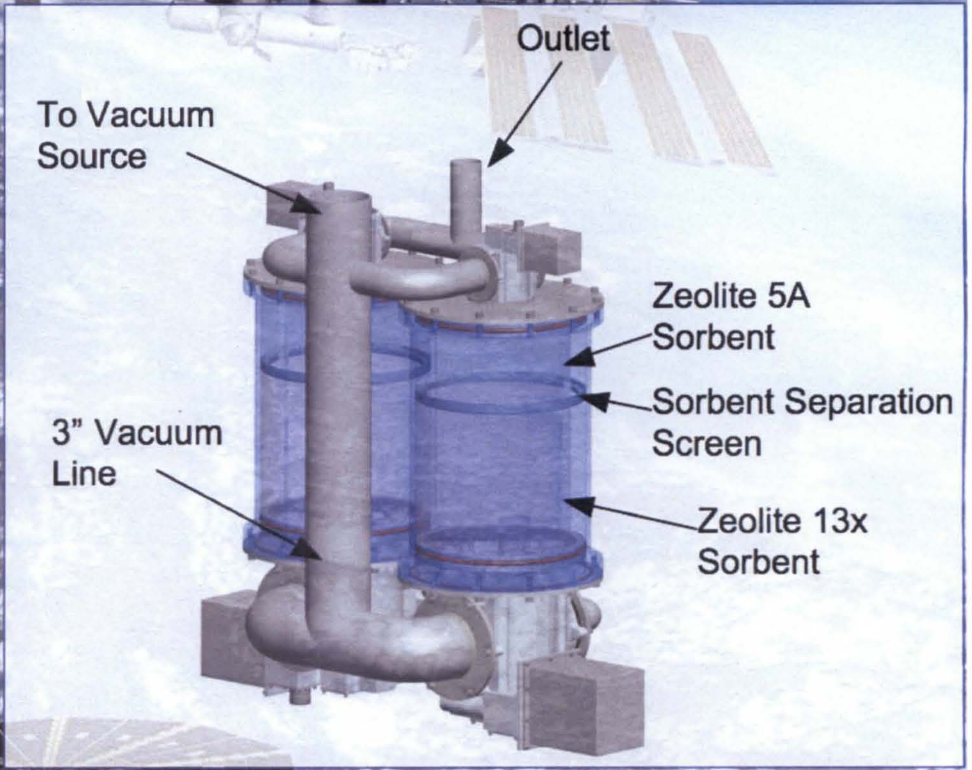
- The International Space Station uses a 4 Bed Molecular Sieve to remove CO_2 from the ISS.
- Anomalies due to a flaw in the containment design have highlighted the need for a more robust sorbent configuration.
- The 4BMS design returns water to the cabin and can either vent CO_2 or store it in an accumulator for subsequent reduction reaction and water recovery



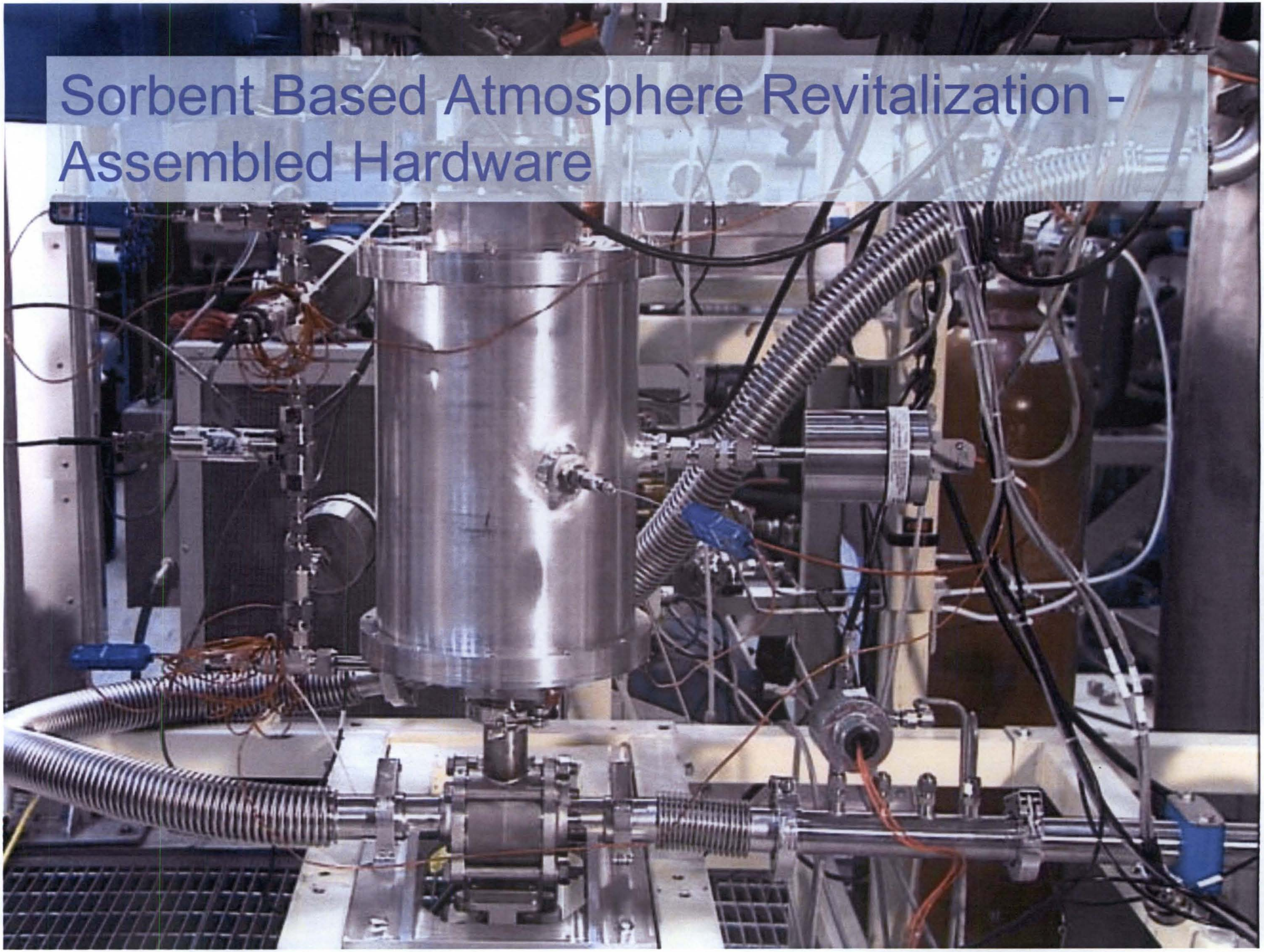


Prototypic CO_2/H_2O Removal System for Orion Under Test at MSFC

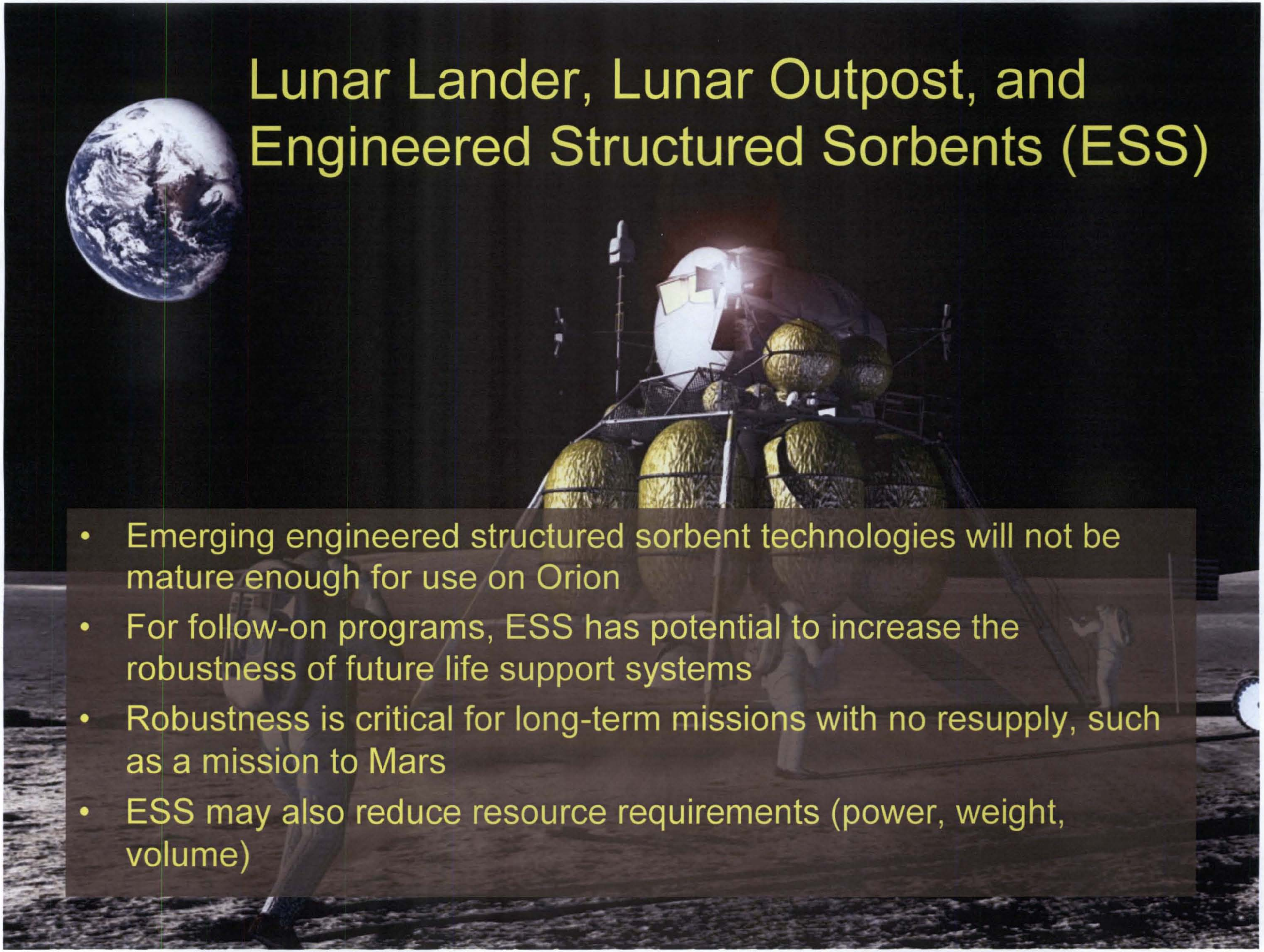




Sorbent Based Atmosphere Revitalization - Assembled Hardware

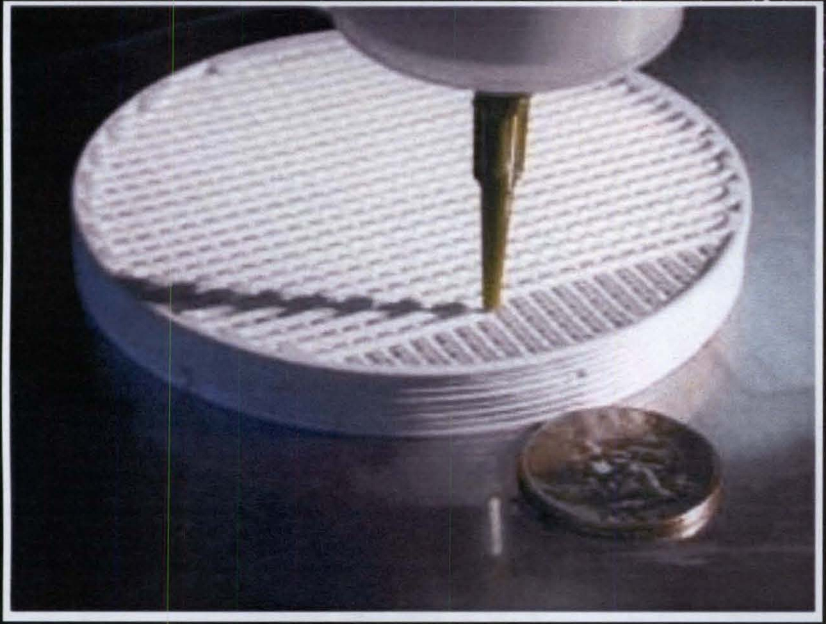


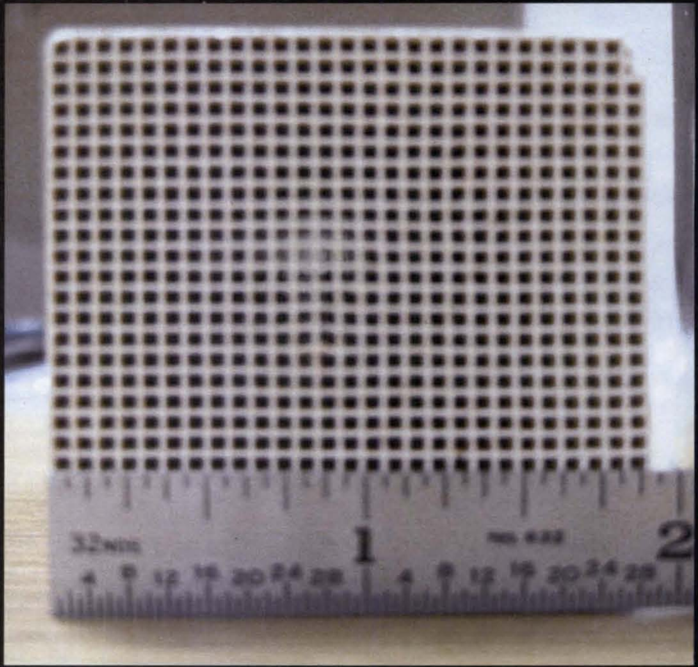
Lunar Lander, Lunar Outpost, and Engineered Structured Sorbents (ESS)



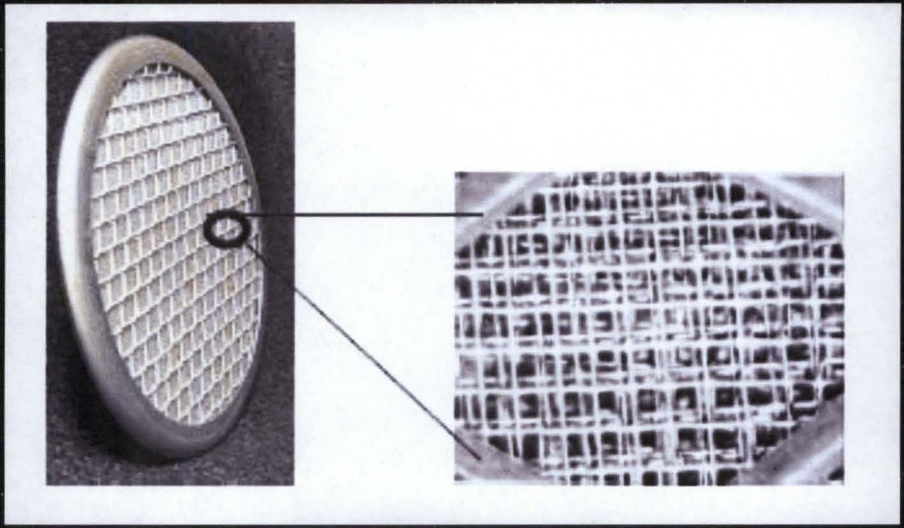
- Emerging engineered structured sorbent technologies will not be mature enough for use on Orion
- For follow-on programs, ESS has potential to increase the robustness of future life support systems
- Robustness is critical for long-term missions with no resupply, such as a mission to Mars
- ESS may also reduce resource requirements (power, weight, volume)

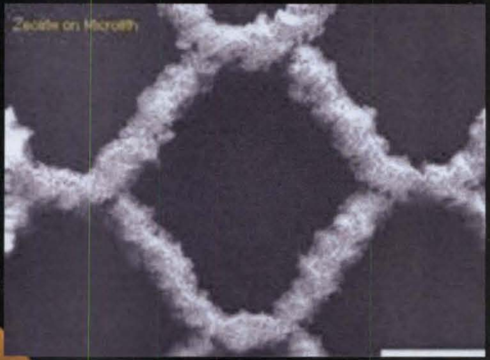
Monolithic Structured Sorbent Technologies

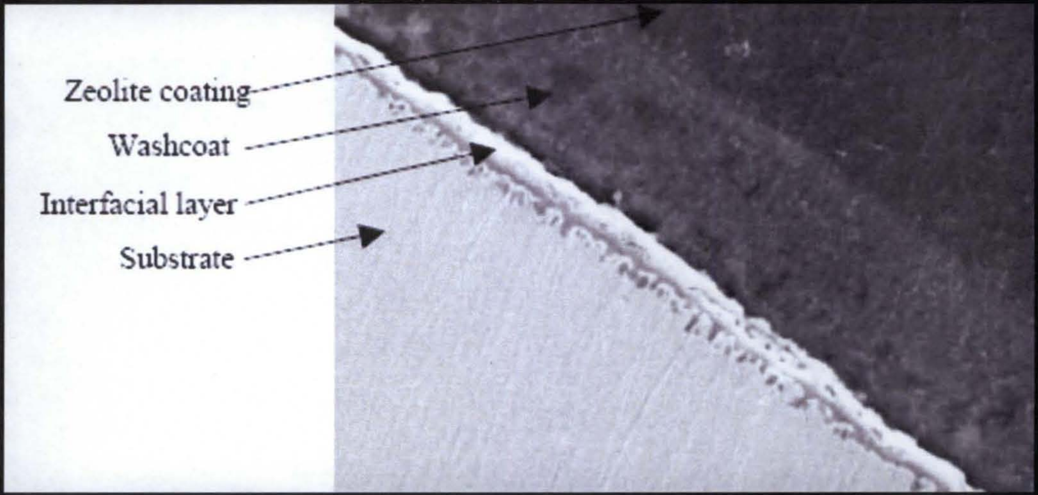




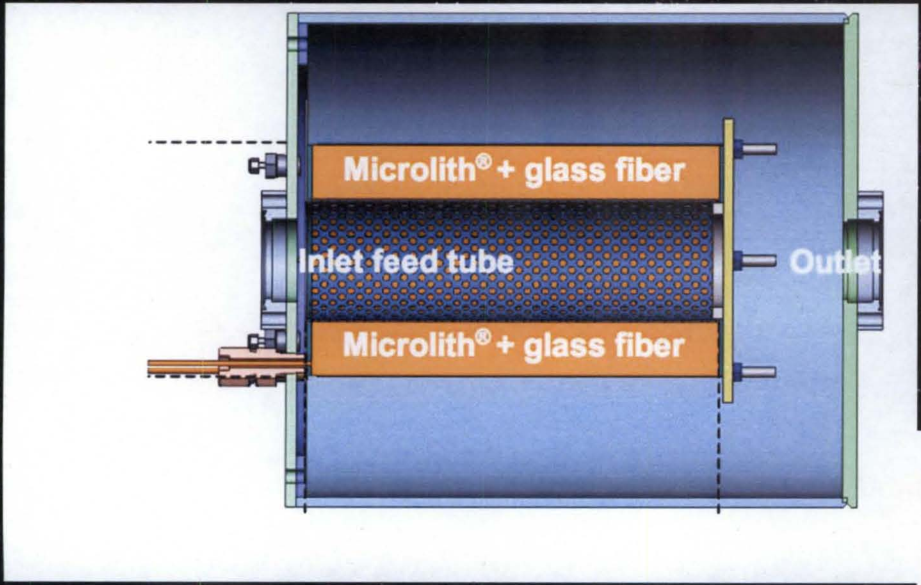
Precision Combustion Metal Microlith®

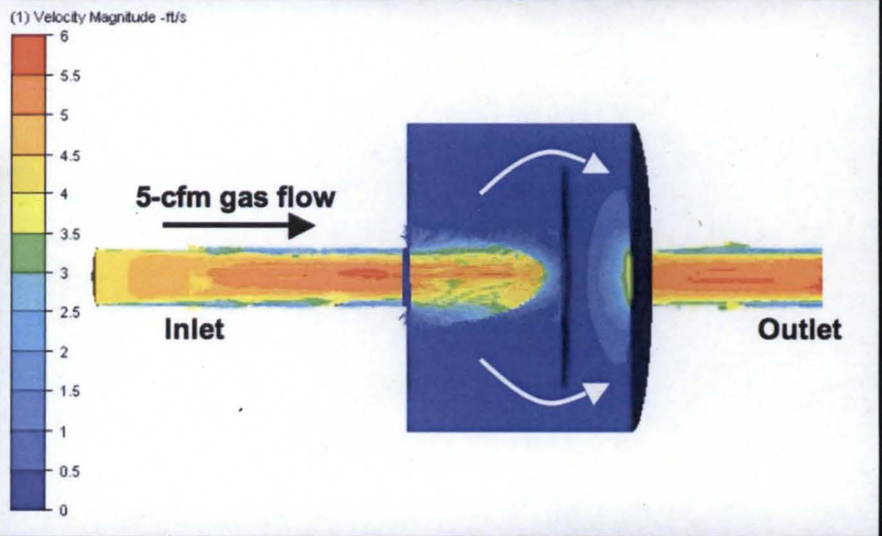




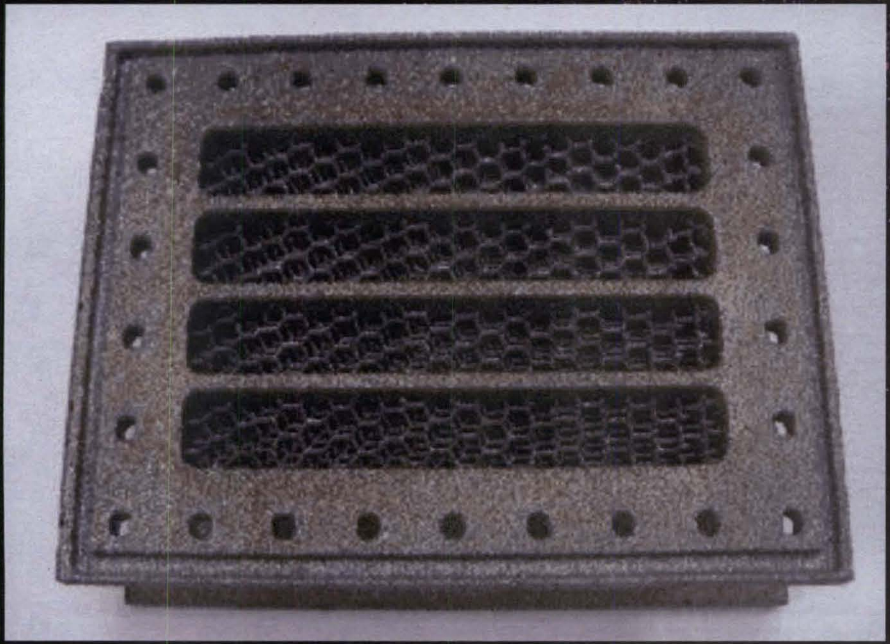


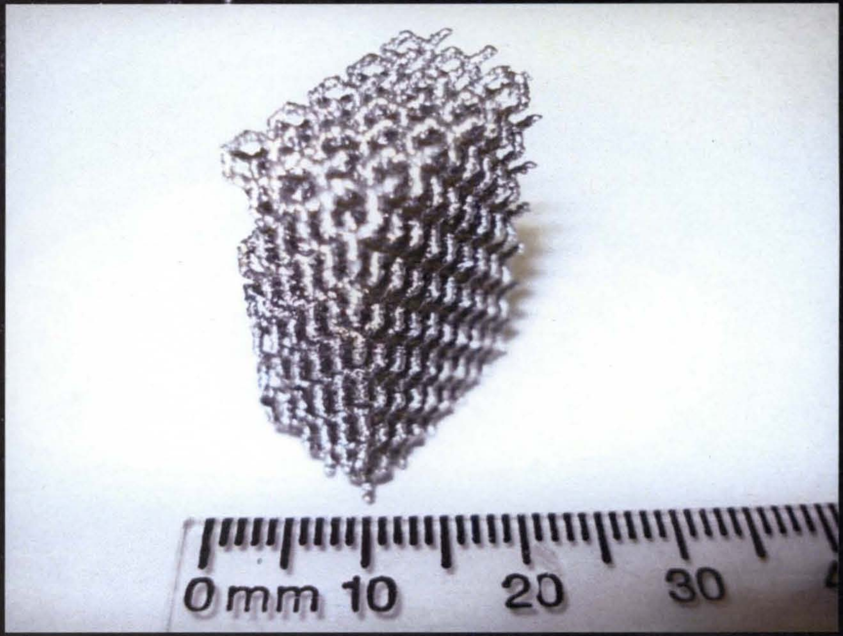
Precision Combustion Metallic Microlith®

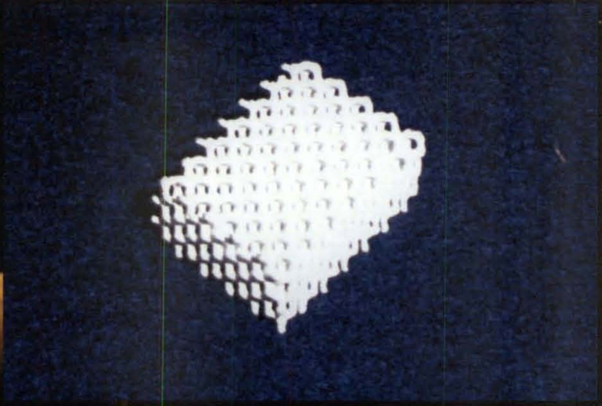


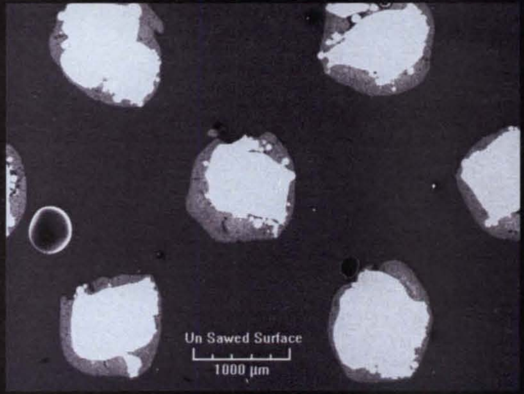


Electron Beam Melting Metallic Structured Sorbent





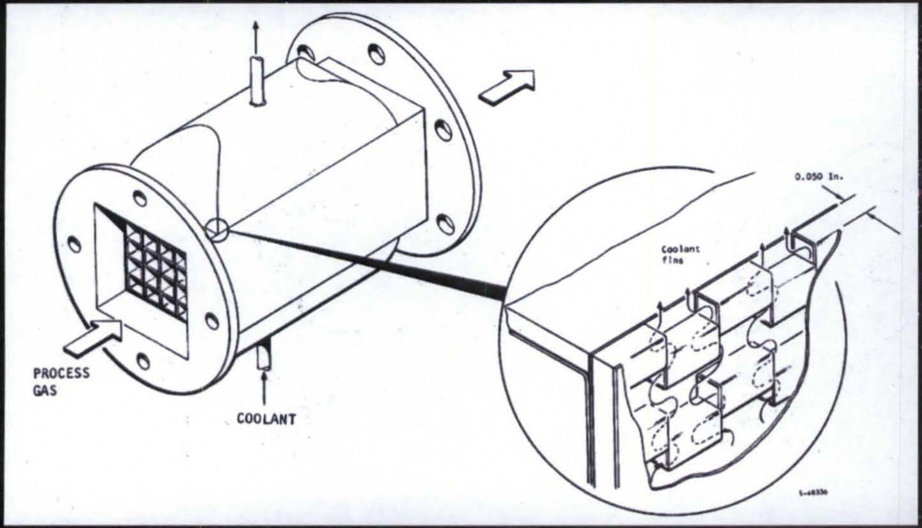




Determination of Regenerative Heating Efficiency Improvements via Simulation

- Metallic Structured Sorbents provide an efficient heat transport path
- Heat of adsorption is a negative influence on sorption removal processes
- Heating during adsorption reduces sorbent capacity - impedes adsorption
- Cooling during desorption increases sorbent capacity - impedes desorption
- Overall effect is a reduction in working capacity
- But, hardware costs (mass and volume) are associated with regenerative heating - *is it worth it*?
- To find out, build COMSOL models of packed bed adsorption process …

Empirical Determination of LDF Coefficient via Simulation of Isothermal Testing



$$\frac{\partial C_i}{\partial t} = D_1 \frac{\partial^2 C_i}{\partial x^2} - \frac{\partial u C_i}{\partial x} - \frac{1-\varepsilon}{\varepsilon} \frac{\partial \overline{q}_i}{\partial t}$$

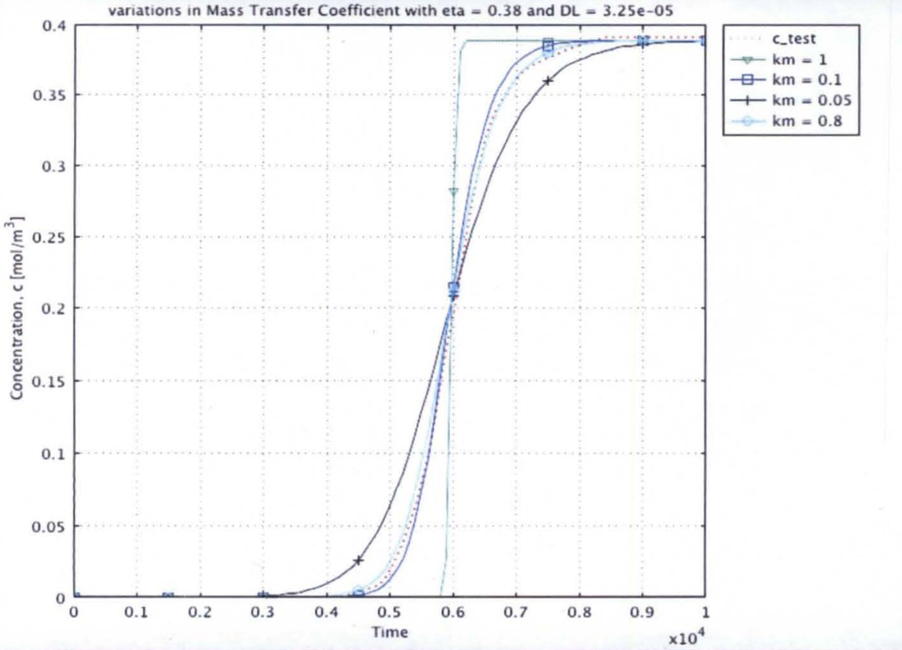
$$\text{at } t < 0,\ C_i = C_{i,0} \text{ for } 0 \le x \le L$$

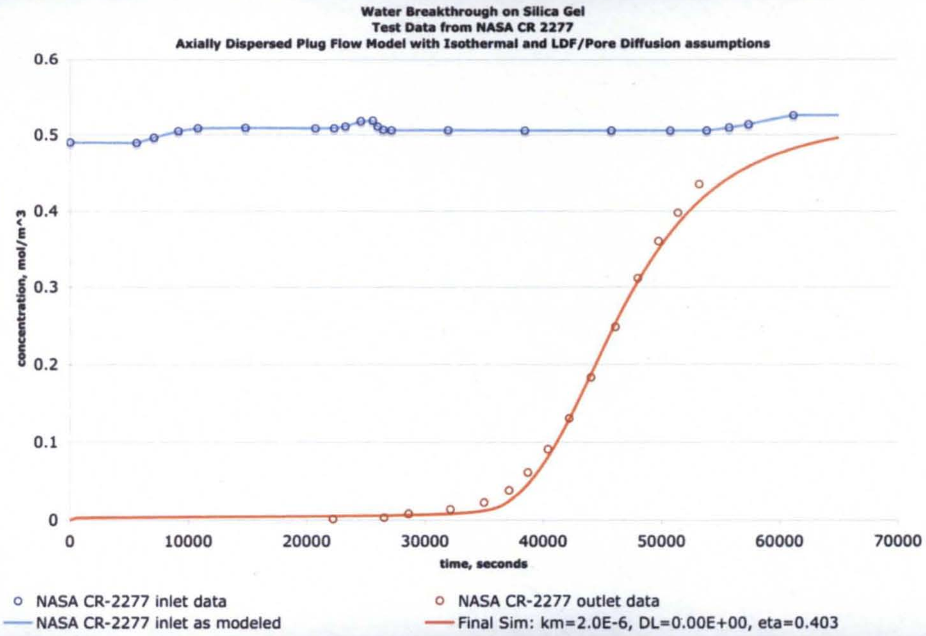
$$\text{at } t < 0,\ \overline{q}_i = \overline{q}_{i,0} \text{ for } 0 \le x \le L$$

$$\text{at } t \ge 0,\ C_i = C_{i,0} \text{ for } x = 0$$

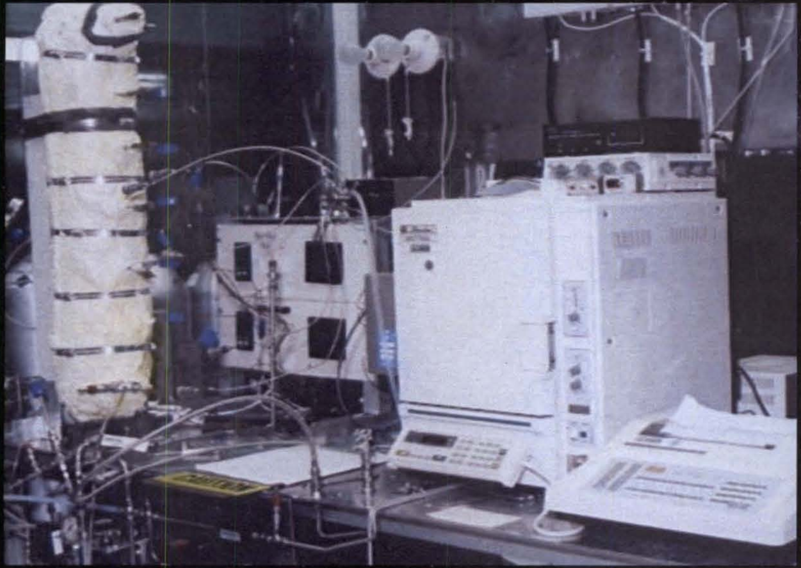
$$\text{at } t \ge 0,\ \partial C_i / \partial x = 0 \text{ for } x = L$$

$$\partial \overline{q}_i / \partial t = k_{\text{ef}} a_s (q_i^* - \overline{q}_i)$$


variations in Mass Transfer Coefficient with eta = 0.38 and DL = 3.25e-05


Water Breakthrough on Silica Gel
Test Data from NASA CR 2277
Axially Dispersed Plug Flow Model with Isothermal and LDF/Pore Diffusion assumptions

Empirical Determination of Heat Transfer Coefficient via Simulation of Thermal Characterization Testing



$$\rho_g c_{pg} \frac{\partial T_g}{\partial t} = k_f \frac{\partial^2 T_g}{\partial x^2} - u \rho_g c_{pg} \frac{\partial T_g}{\partial x}$$

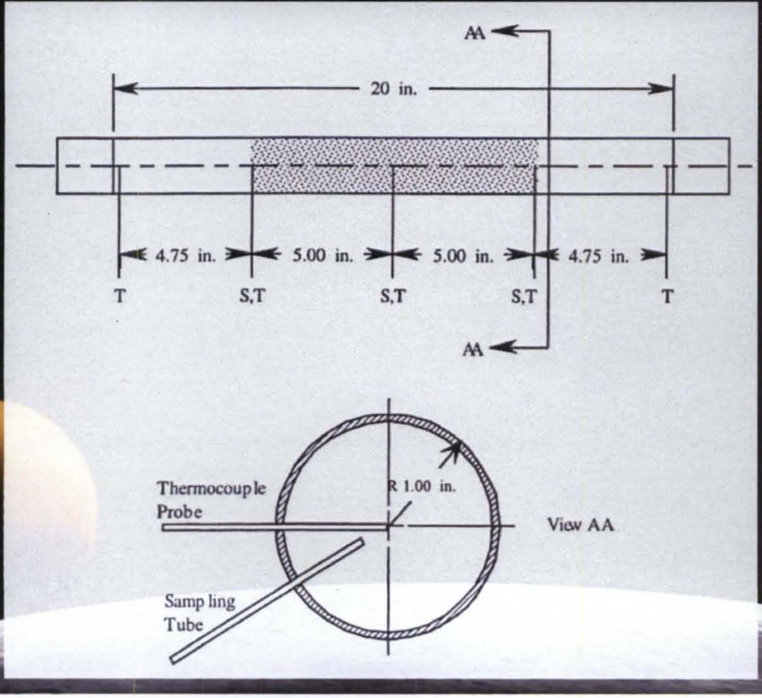
$$+ \frac{1-\varepsilon}{\varepsilon} h_s a_s (T_s - T_g) - \frac{4h_w}{\varepsilon d}(T_g - T_w)$$

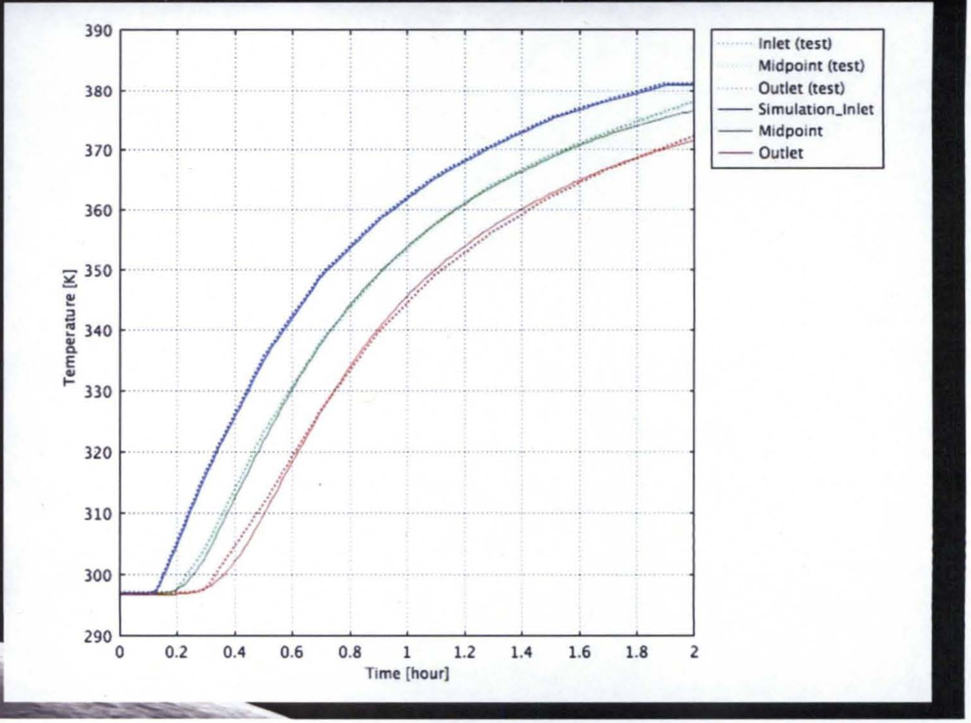
Boundary and initial conditions:

at $t < 0$, $T_g = T_{g,0}$ for $0 \le x \le L$

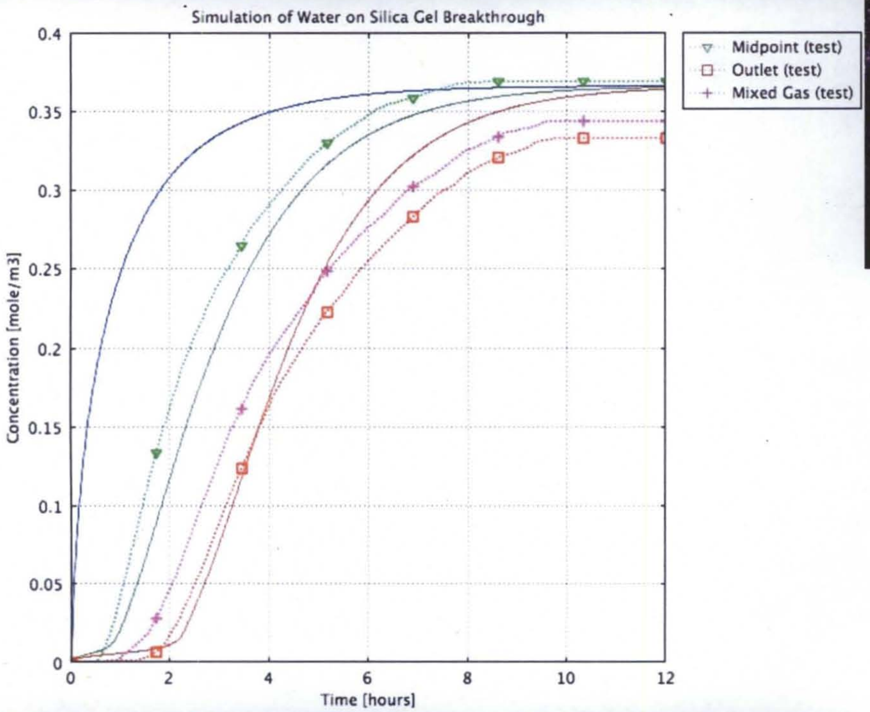
at $t \ge 0$, $T_g = T_i$ for $x = 0$

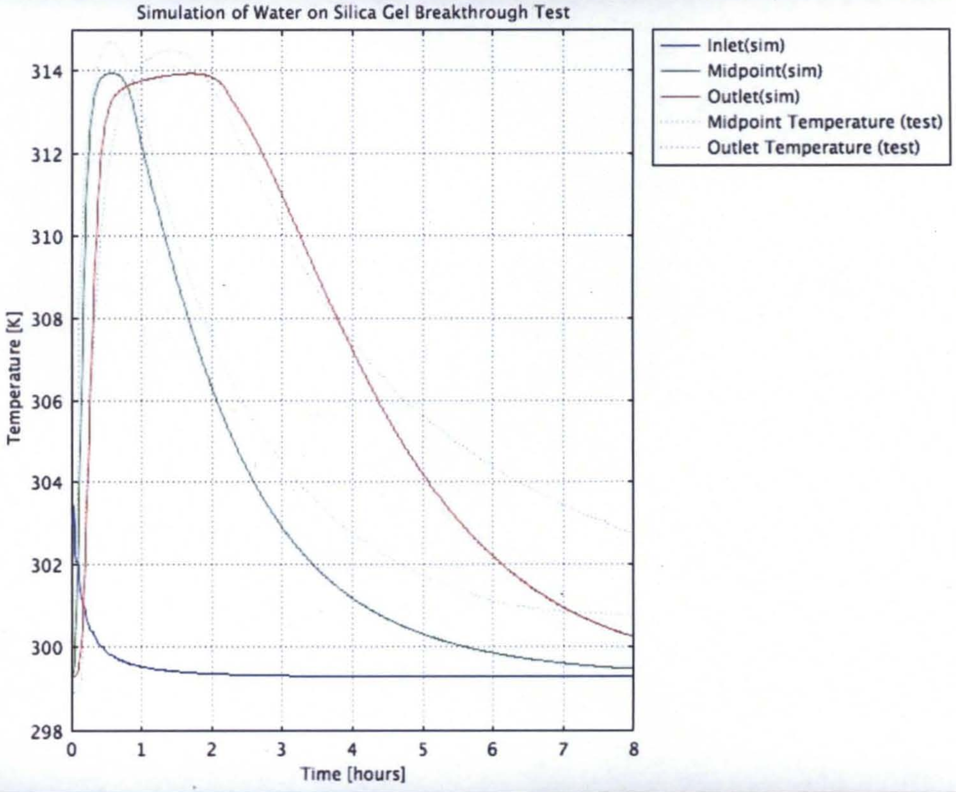
at $t \ge 0$, $\partial T_g / \partial x = 0$ for $x = L$



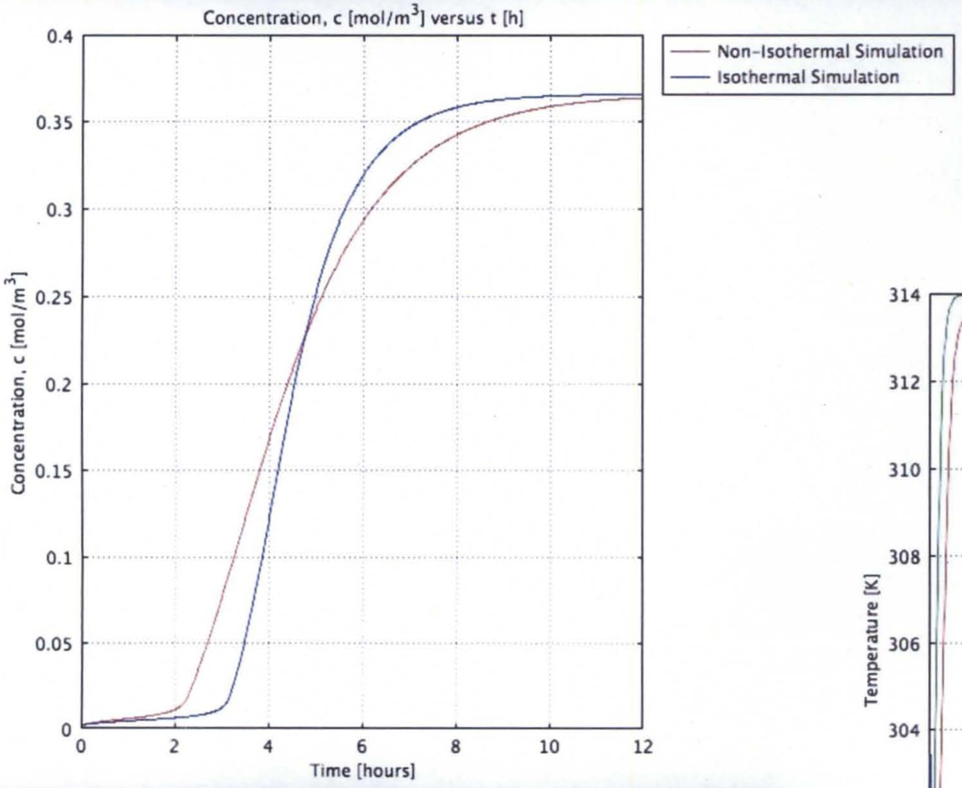


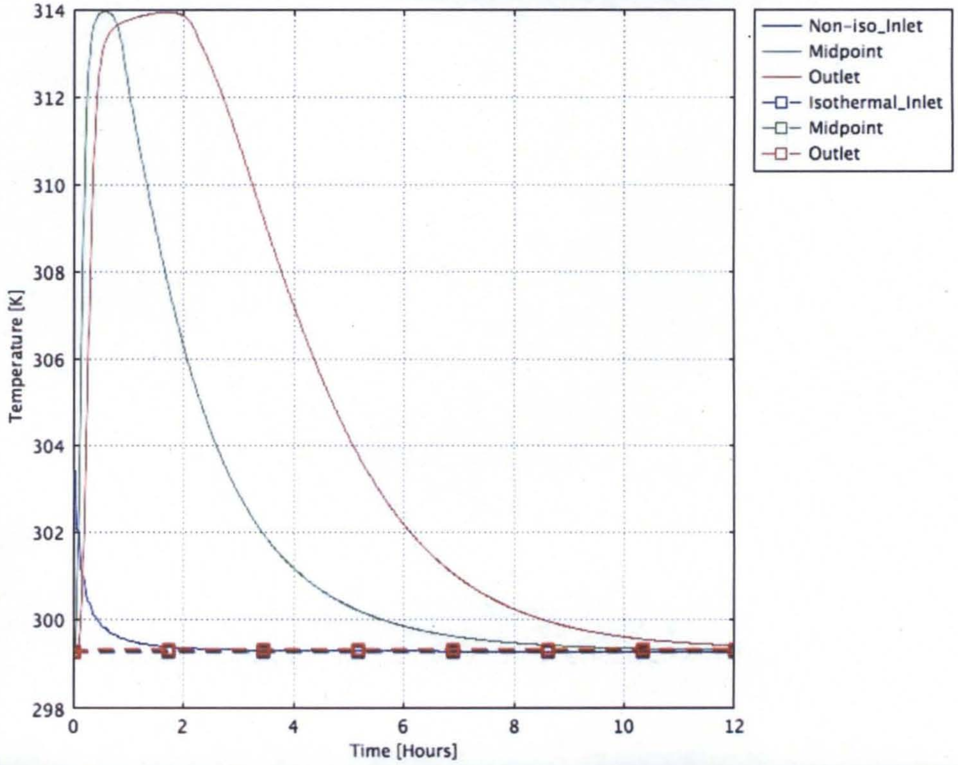
Simulation of Water Adsorption on Silica Gel including Heat of Adsorption Effects



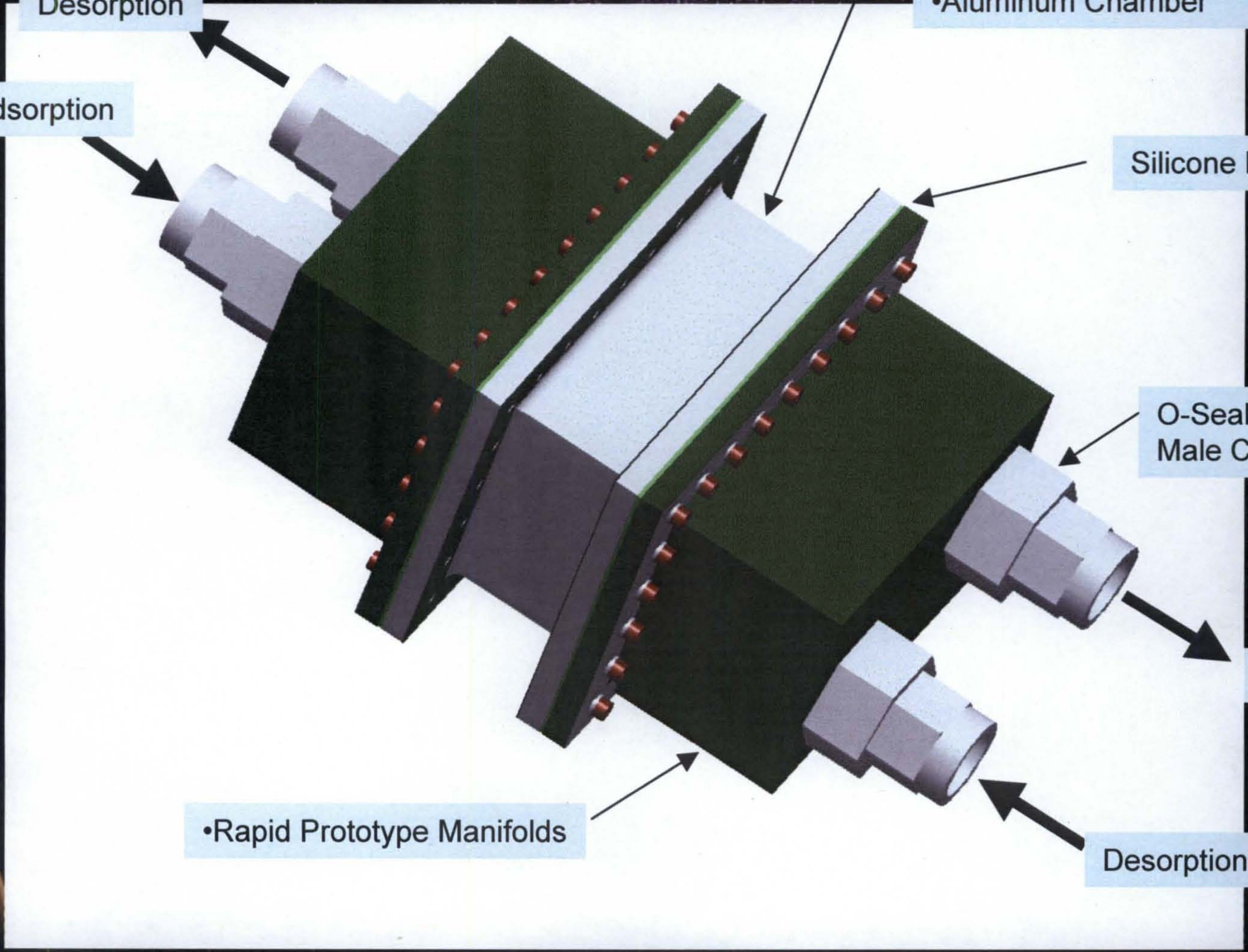


Simulation of Theoretical Efficiency Improvement via Regenerative Heating





Regenerative Heating of Physical Adsorbents



Desorption

Adsorption

- Rapid Prototype Chamber
- Aluminum Chamber

Silicone Rubber Gasket

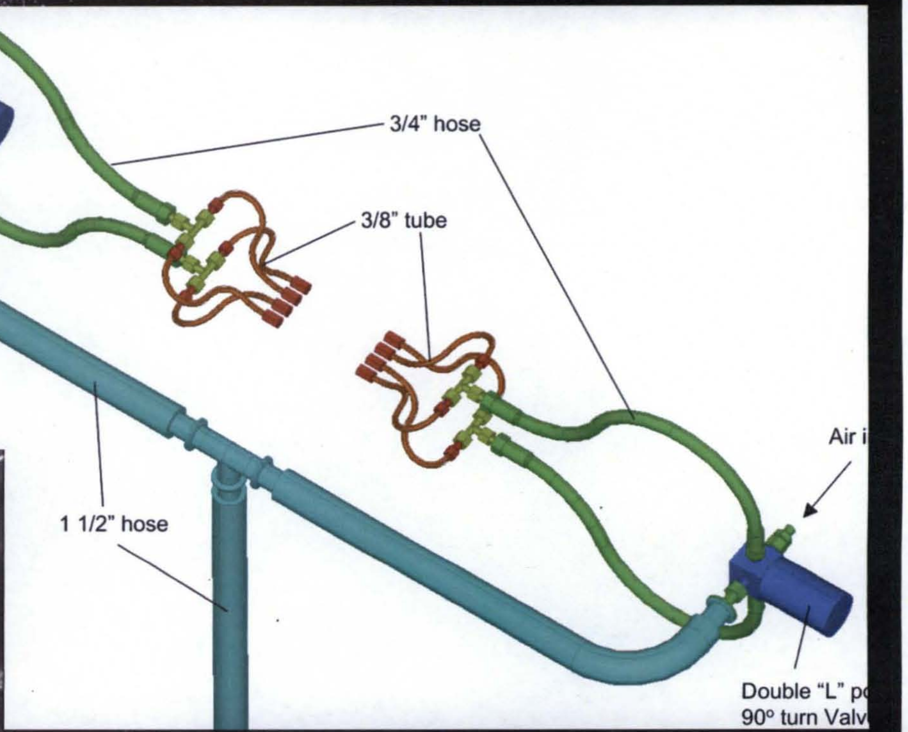
O-Seal Straight Thread Male Connector

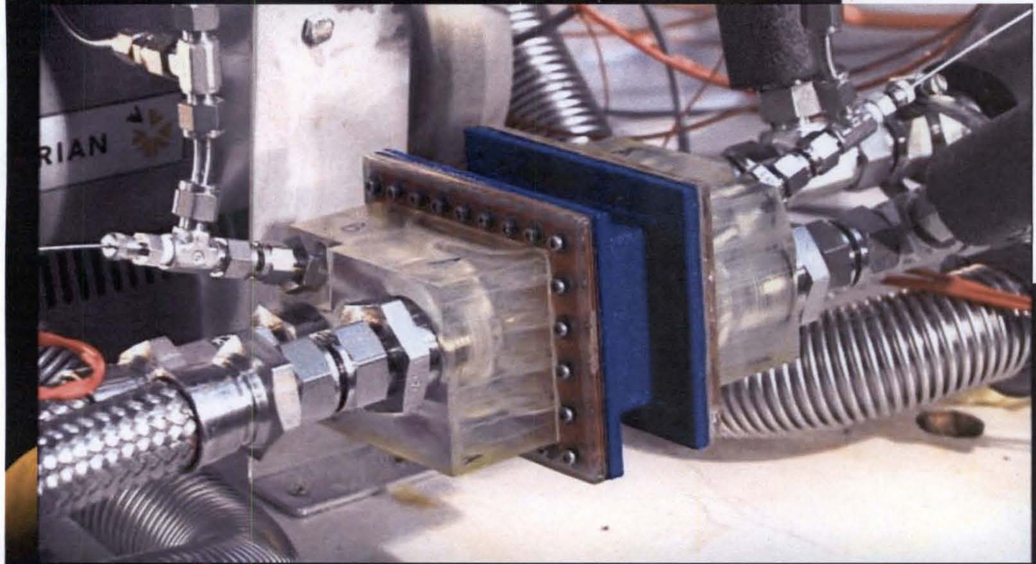
Adsorption

Desorption

- Rapid Prototype Manifolds

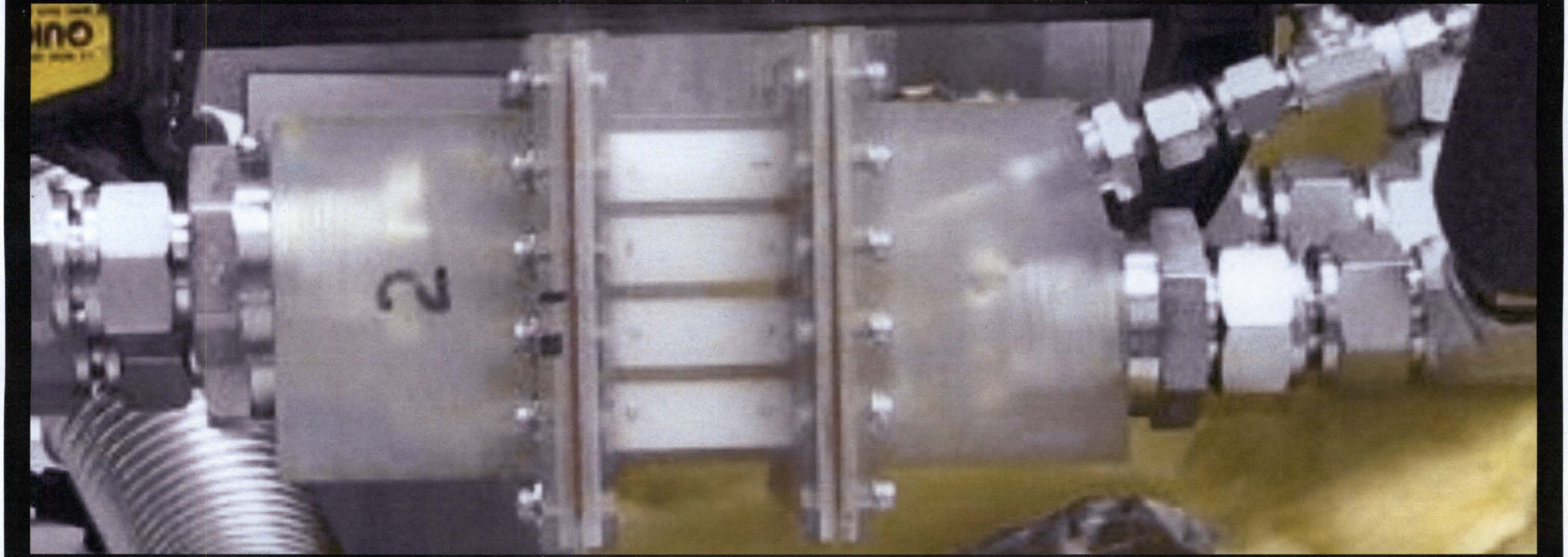
Subscale Adsorbent Bed Testing



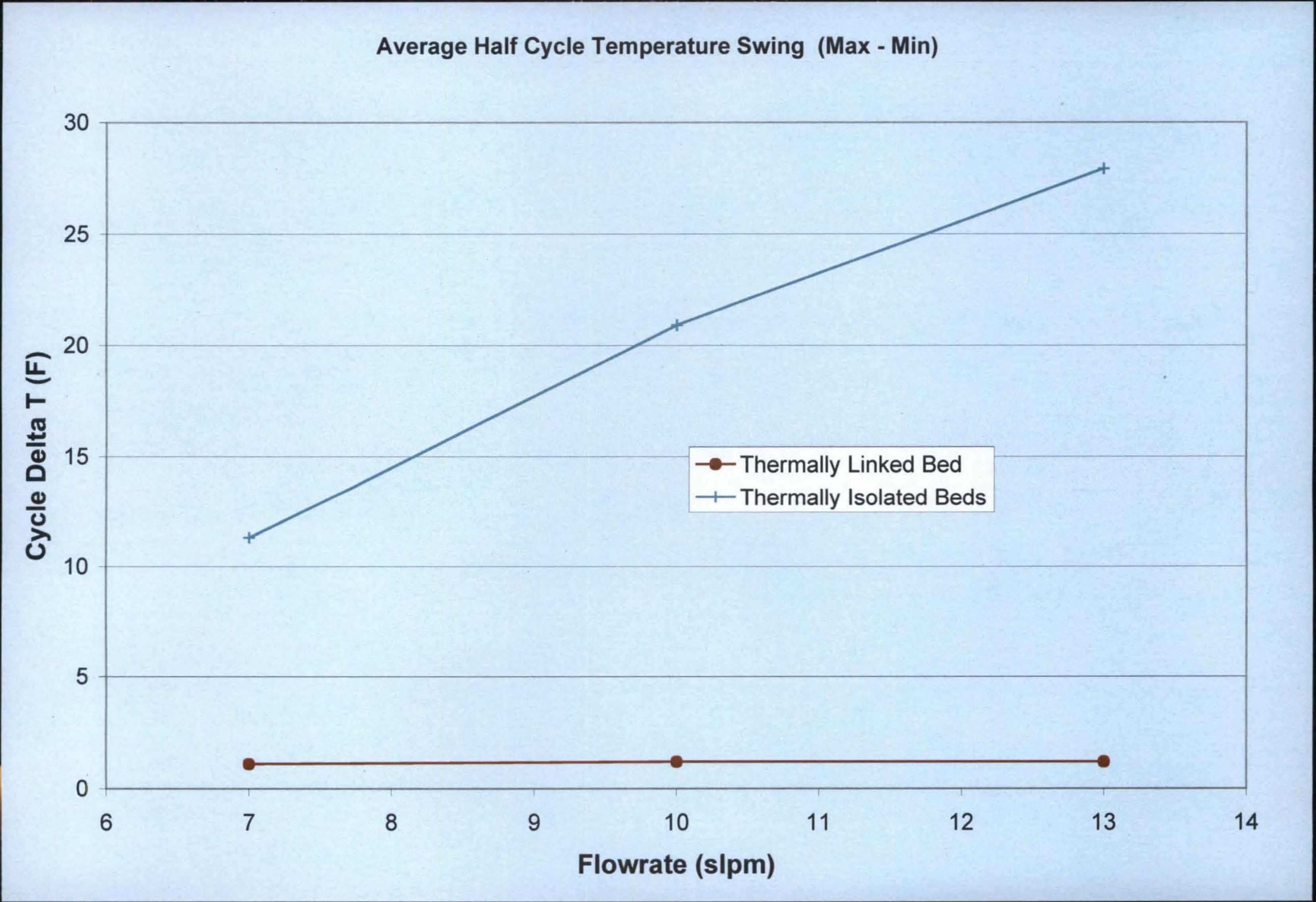


Regenerative Heating of Physical Adsorbents:

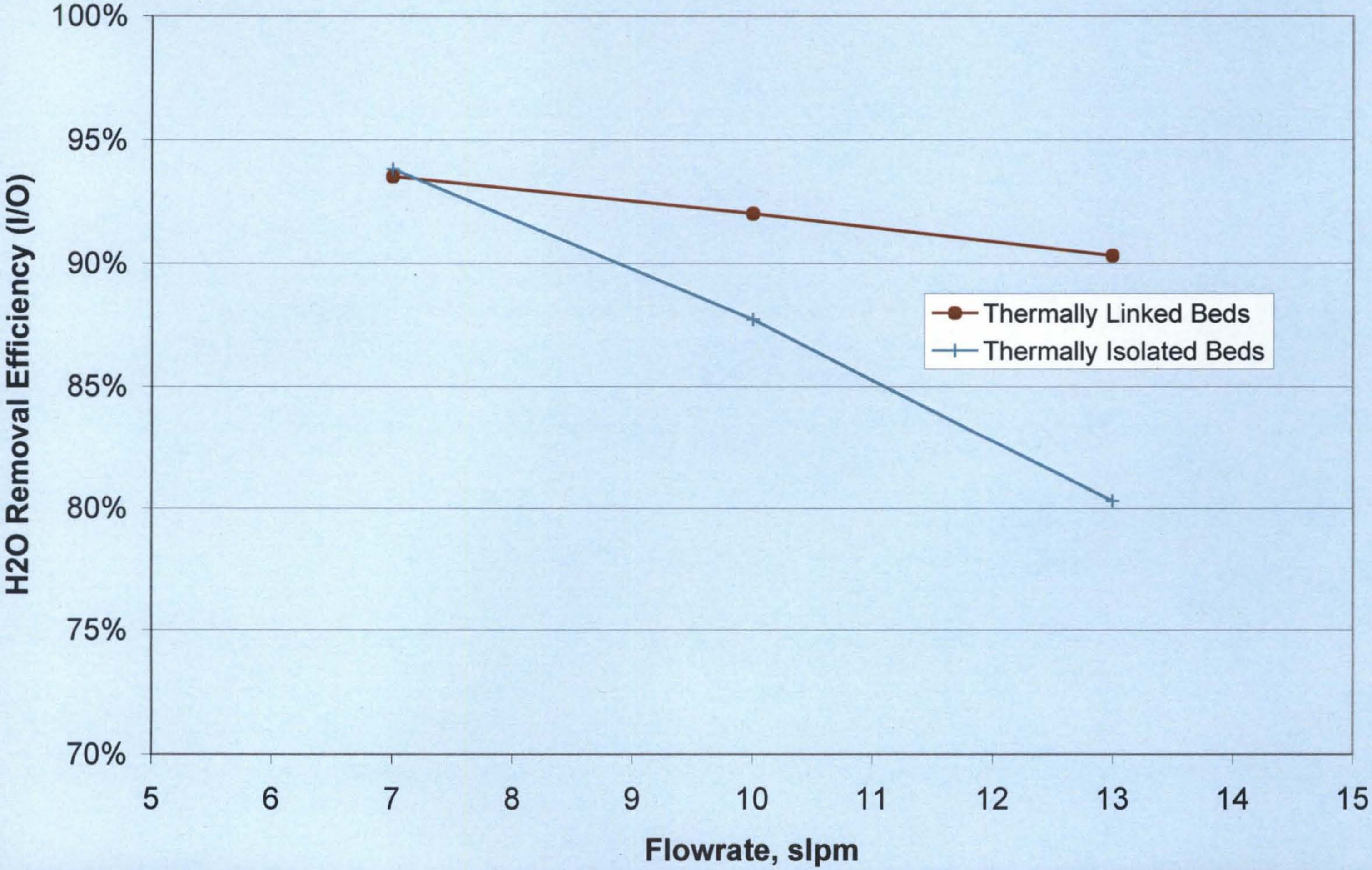
(Thermal Isolation Testing Shown)



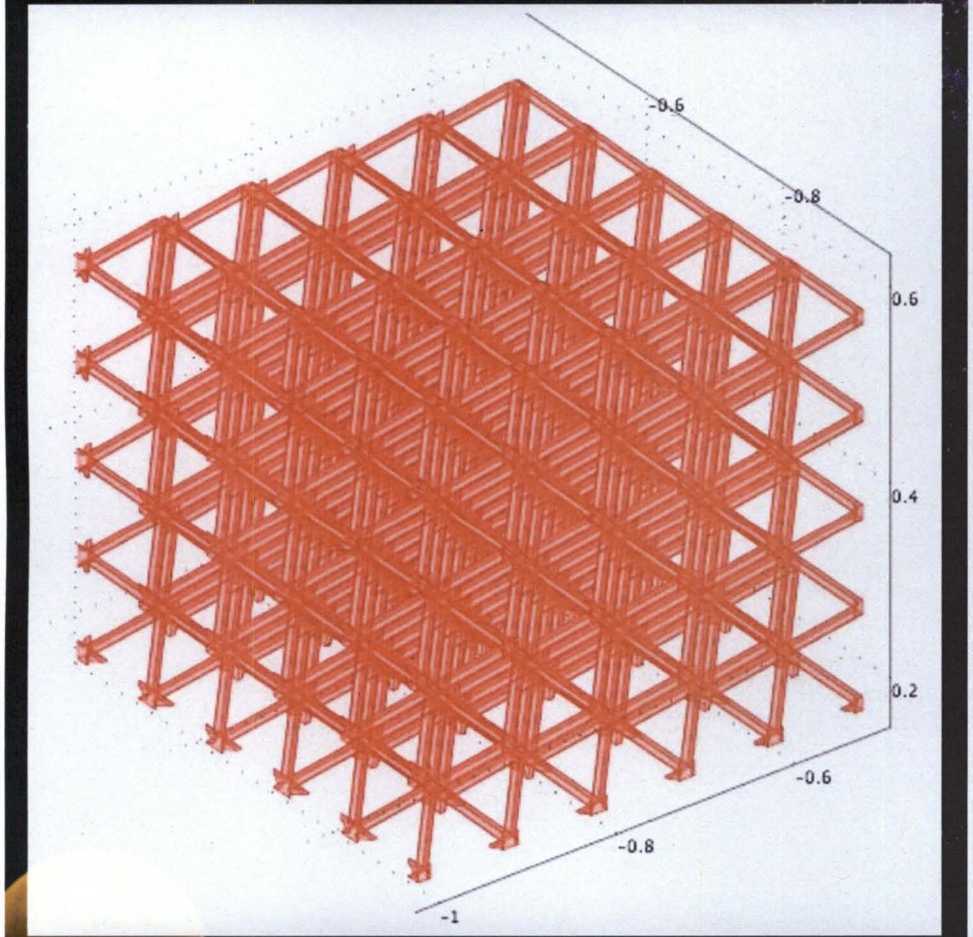
Subscale VSA Test Results

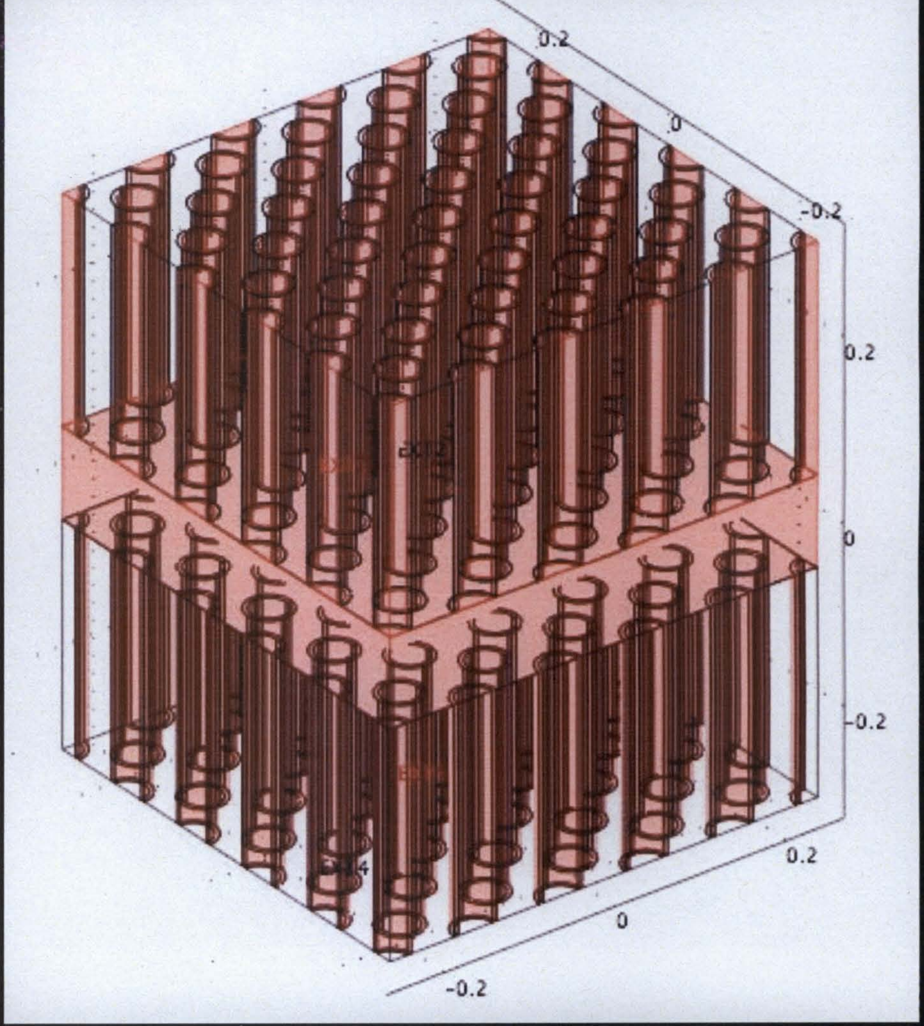


Subscale VSA Test Results

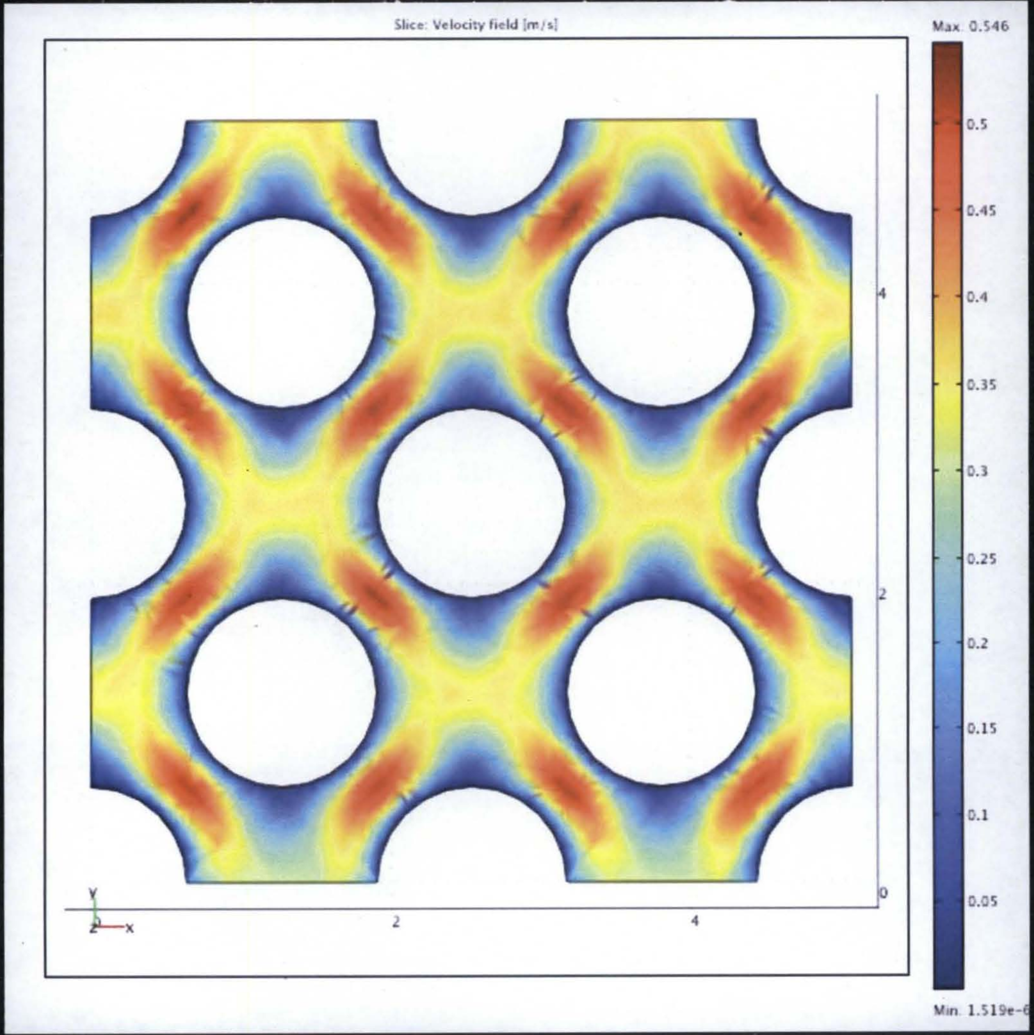


Fluid Flow Through Structured Sorbent Lattice

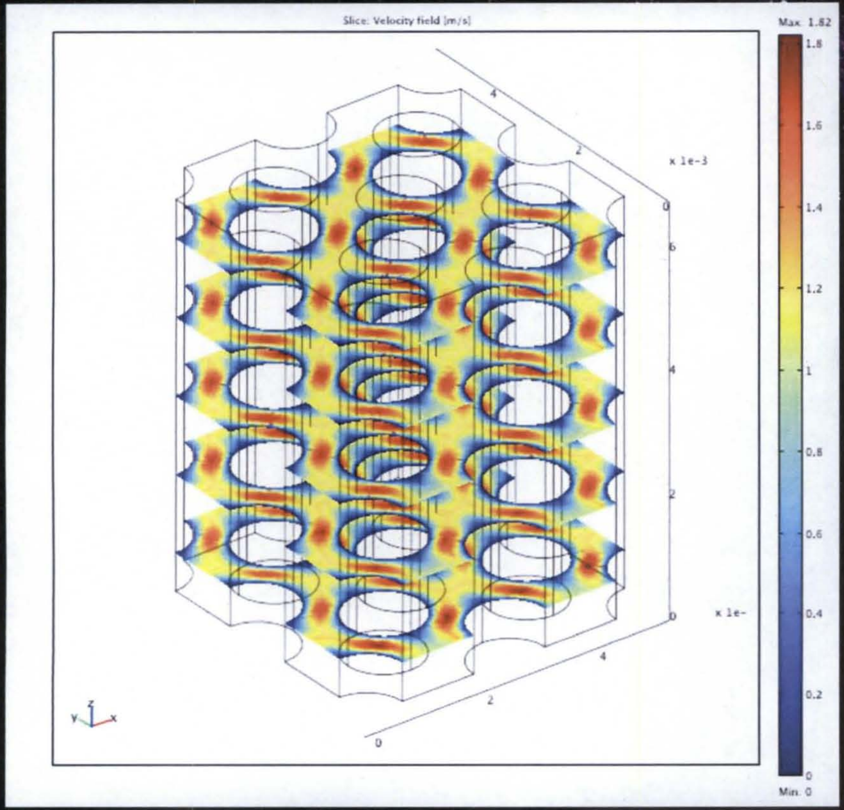


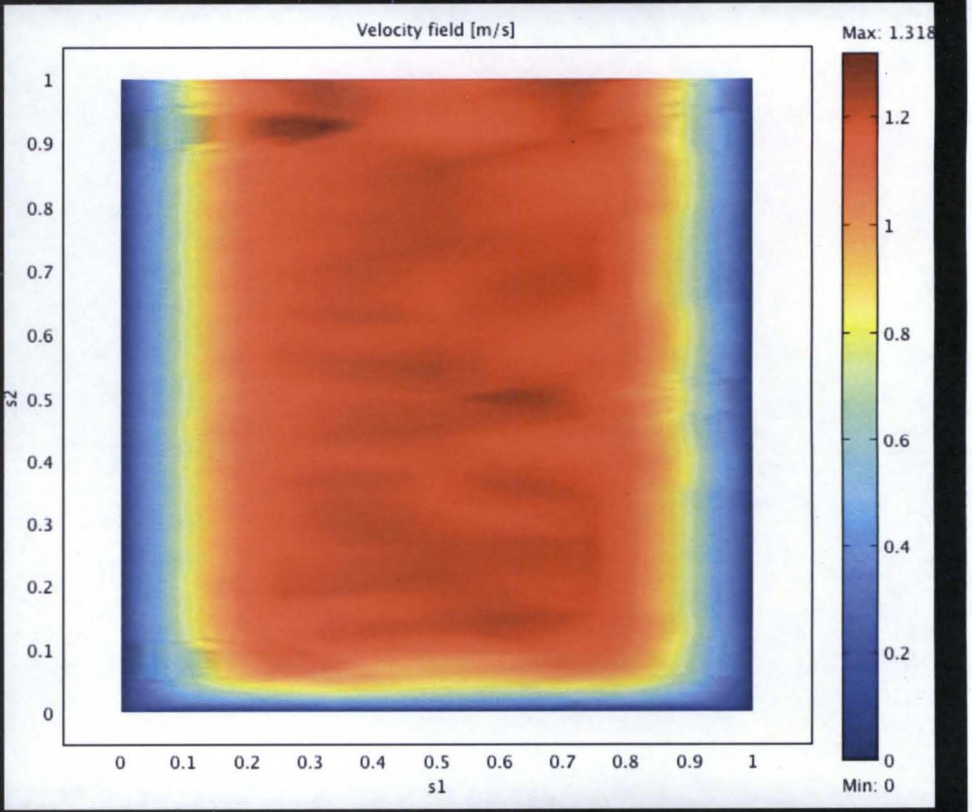


Fluid Flow Through 2-D Structured Sorbent Lattice



Fluid Flow Through 3-D Structured Sorbent Lattice





Continuing Work

- Develop multiphysics simulation of existing subscale tests with EBM and reticulated aluminum foam test articles
- Optimize process parameters (cycle time, flow rate, etc.) for existing test articles via simulation
- Optimize design of lattice and structure design (wall thickness, lattice geometry, diameter, and spacing, etc.) via simulation
- Fabrication and test of optimized regenerative heating design in sub-scale and full-scale configurations
- Continue comparative testing of alternate Engineered Structured Sorbent approaches with using packed bed performance as baseline